WHY WON'T IT TAKE THAT ?
MCP CONTROL DEVICE INVOKES MORE THAN ONE AUTOPILOT BEHAVIOR

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ABSTRACT:

A class of automation surprises can be attributed to the fact that the same mode control panel (MCP) knob results in two distinct autopilot control behaviors depending on the situation. For example, one behavior flies to, and captures, the MCP altitude, the other behavior breaks the capture and flies away from the MCP altitude. This paper describes a formal modeling technique for identifying MCP control devices that change their function in different contexts. This paper also describes how the contents of the formal modeling technique can be used to develop training and to set criteria used for certification.

Keywords:
Automation surprise, modal user-interface, formal model, human factors, certification criteria.

1 INTRODUCTION

Several researchers have provided case studies of automation surprises that occurred following pilot interaction with the mode control panel (MCP) or flight control unit (FCU) (Palmer, 1995; Degani & Heymann, in press; Javaux, 1998). An automation surprise was also documented in a recent National Transportation Safety Board (NTSB) Safety Recommendation (NTSB, 1999). In all of these scenarios the pilot *was surprised by the trajectory of the aircraft as commanded by the autopilot*. Sherry, Feary, Polson, & Palmer (in press-a) described a hypothetical representative example of this class of automation surprise:

> **Hypothetical Example:** "When flight xxx was cleared to descend to 20,000 ft, the first officer initiated a descent via the autopilot. With approximately 1,200 ft left in the descent, the captain became concerned the airplane might not level off at the assigned altitude and instructed the first officer to slow the descent rate. The first officer adjusted the MCP vertical speed wheel; however this maneuver proved ineffective. The captain then took manual control of the airplane, …. then disconnected the autopilot …"

This example, highlights two prominent issues in the design, training, and operation of complex automation:

(1) What is it doing now ? What is it going to do next ?: "…the captain became concerned the airplane might not level off at the assigned altitude," describes a phenomenon in which operators were confused by the behavior of the automation and questioned what the system was doing, and more importantly, what it was going to do next. In this case the pilot/automation system failed to establish a shared understanding of the intention of the automation. See Sherry, Feary, Polson & Palmer,(in press-a) for an analysis of this phenomenon.

(2) How do I convey pilot goals to the automation ?: "…the captain …instructed the first officer to slow the rate of descent. The first officer adjusted the MCP vertical speed wheel; however this maneuver proved ineffective," describes a phenomenon in which the crew were unable to convey their trajectory goals to the automation. In this case the interface between the pilot and automation failed to provide adequate affordances for the pilot to convey their goals to the autopilot.

This paper analyzes the second phenomenon described in the hypothetical example, dealing with issues of unambiguously conveying pilot's goals to the automation. A formal model of the behavior of the autopilot explicitly identifies the specific control devices on the MCP that result in more than one autopilot behavior when selected. The paper also demonstrates how the contents of the formal model provide the basis for training pilots to use "modal" MCP control devices. Guidelines for the design and a recommendation for certification of MCPs are also discussed.

2 AUTOMATION SURPRISES & APPROXIMATE MENTAL MODELS

Norman (1988) proposed that operators of automated systems form "mental models" of the way the system behaves and use these models to guide their interaction with the system. This interaction with the automation (and much other human behavior) can be thought of as a continuous process of cyclic interaction (Monk, 1999; Card, Moran, & Newell's, 1983; Norman, 1988; and Anderson, 1993). To achieve a trajectory goal, the pilot performs a set of actions that lead to changes in the automation, which in turn causes changes in the environment. Evaluation of the state of the environment leads to reformulation of the pilot's goals and further action, leading to a new state of the environment, and so on.

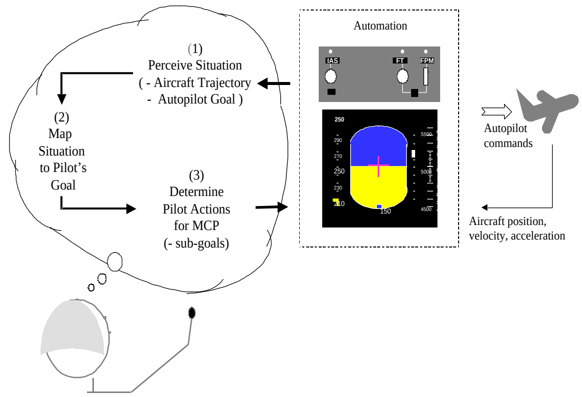
Sherry, Feary, Polson, & Palmer (in press-a) described a pilot's interaction with the autopilot as a cyclic process (Figure 1). Based on information from the environment, the pilot formulates a definition of the perceived situation (1). This situation is used to determine appropriate goals (2). The goals are then mapped to a sequence of actions on the MCP (3). In many cases, the sequence of actions themselves lead to the formulation of sub-goals and sub-actions as described in hierarchical task models such as GOMS (Kieras and Johns, 1996) and OFM (Callantine & Mitchell, 1999).

The focus of this paper is the pilot's failure to map a pilot's goal to a set of actions on the MCP (block 3). This failure may be the result of the absence of appropriate knowledge in the pilots head, or when the knowledge is present, a failure in cognition, described by Norman (1988) as an "action slip." Incomplete and inaccurate training material results in gaps in a pilot's knowledge. Inadequate affordances on the mode control panel fail to constrain pilot's actions, do not reinforce correct pilot behavior, and result in action slips.

2.1 Conveying Pilot Goals to the Automation: Placing Knowledge in the World

The need to place knowledge in the pilots head to convert pilot goals to actions on the MCP,[1] can be effectively eliminated by "placing knowledge in the world" using a label following strategy (Polson & Lewis, 1990). Mode control panels designed in this manner have unique, labeled, control devices for each of the pilot goals. Examples are the ALT HOLD or FLCH buttons on the Boeing B7X7 MCPs. Hutchins (1994) Integrated Mode Management Interface (IMMI) is designed to provide similar direct manipulation of waypoints and constraints in the flightplan. Riley (1998) Modeless Control Panel provides a user-interface that allows pilots to convey ATC instructions directly to the automation by entering ATC-like phases, from a list, into a one-line wordprocessor on the MCP.

[1] It assumed in this discussion that the pilot has selected the appropriate goal based on the situation and is simply trying to convey this goal to the automation.



(1) Situation, (2) goal, and (3) action sequence of pilot interaction with automation. Boxes represent knowledge required by the pilot.
Figure 1

2.2 Conveying Pilot Goals to the Automation: Placing Knowledge in the Head

Operators of automation are required to carry knowledge in their heads when the control devices on the user-interface exhibit context-based dynamic behavior (Sellen, Kurtenbach, & Buxton, 1992). For example, operator selection of the MCP/FCU push-button switches used to toggle between the Vertical Speed window and Flight Path Angle window, or the button that changes the units in the Speed window between CAS and Mach, must be unambiguously understood by the operator.

Another case when knowledge to convey an operator goal to the automation must be placed in the head of the pilot is when the user-interface is modal, not by a pilot action in switching the user-interface mode, but by an *autonomous change made by the automation*. The MCP/FCU exhibits this type of behavior with the vertical speed wheel on the DC-9/MD-80 aircraft (Palmer, 1995), the altitude knob on the B757/767 and B737 (Degani & Heymann, in press). The changes in the context perceived by the autopilot result in autonomous modification of the user-interface mode by the autopilot. In this way the same pilot action on the MCP results in different autopilot behavior. Knowledge of the behavior of these control devices must be unambiguously understood by the pilot.

2.3 Problems Putting Knowledge in the Head: Approximate Mental Models

In the absence of simple, consistent, and communicable descriptions of the behavior of the cockpit automation, pilots will (and do) create their own models of this behavior (Vakil & Hansmann, 1999). These ad-hoc mental models are, at best, approximations of the behavior of the actual avionics and directly contribute to automation surprises by providing predictions that are different than the actual behavior of the automation.

The mental models of pilots are approximations for three reasons. First the training materials provided in the form of Flight Crew Operating manuals (FCOMs) provided by the manufacturers and airlines are incomplete and do not reflect the underlying conceptual model of the behavior (Vakil & Hansmann, 1999). Second, the content of the cockpit displays does not provide sufficient information to infer the behavior of the automation even when it is trained completely (Hutchins, 1994). Third, pilots develop approximate models of the behavior of the automation due to naturally occurring cognitive processes that simplify and generalize rules in memory (Javaux, 1998). This simplification of the rules takes place as a result of infrequent use and generalization of similar behaviors.

This paper describes how a formal model of the behavior of the autopilot, with operationally meaningful labels of goals, can be used to identify ambiguity in the autopilot behavior resulting from selection of each control device on the MCP. When the "modal" nature of the design cannot be overcome, the model explicitly defines the knowledge that must be placed in the pilot's head.

3 METHOD OF ANALAYIS: SGA MODEL

The SGA model, a variation of the Operational Procedure Model (Sherry, 1995), layers a semantic goal model over a formal situation-action model of a finite state machine:

Situation $= f$ (state of env. from system inputs) (1)
Goal $= f$ (situation) (2)
Outputs $= f$ (goal, actions) (3)

The conditions of input parameters to the automation determine the situation perceived by the automation in equation (1). The situation is used to determine the appropriate goal in equation (2). Based on the goal, a prescribed set of actions are executed to generate values for the outputs in equation (3). By definition, the automation will respond, by executing a sequence of actions, to all possible combinations of conditions on the inputs (whether by design or by default).

3.1 Analyzing User-Interfaces Using SGA model

User-interface control devices, such as the knobs, wheels, and buttons on the MCP, are a subset of the inputs in the SGA model. These parameters typically play a significant role in the model as trigger conditions that directly cause changes in automation's goal. By listing the control devices that invoke each of the automation's goals, the SGA model can be used to identify when the user-interface has:

- Duplication or Shortcut: *more than one control device that invokes the same goal*
- Autonomous Modal Behavior: *a single control device that is context dependent and will invoke different autopilot goals in different situations*

When the behavior of modal control devices cannot be eliminated from the design, the situation definitions in the SGA model can be used to ensure sufficient information is displayed so that the pilot can distinguish between the different control device "modes". The SGA model also provides the content for pilot training that enables the pilot to build and maintain proficiency in the operation of the control devices.

4 CASE STUDY: ANALYSIS OF MODERN AUTOPILOT MODE CONTROL PANEL

An SGA model of a modern autopilot was constructed and used to analyze the effectiveness of the MCP of the NASA Research Autopilot (Sherry, Feary, Polson, & Palmer, 1997).

The autopilot SGA model was derived from design logic diagrams and the actual autopilot software. The inputs to the software and their conditions were identified. Each unique combination of input conditions was labeled with a *situation* description. The possible combinations of pitch mode, thrust mode, altitude target, speed target, and vertical speed target were also identified. The combinations of output actions were labeled with an *action* description.

Each possible combination of input conditions (situations) was mapped to a legal combination of outputs (actions). This created situation-action pair rules. Operationally meaningful, g*oal* descriptions were assigned to each situation-action pair. Where possible the goal description reflected Air Traffic Control nomenclature, such as "climb and maintain XXX thousand feet."

Several iterations of the model were required to yield a model with operationally meaningful input conditions and operationally meaningful goal descriptions. A sample of the autopilot goals for up-and-away operations (above 1500 ft) are listed below. A subset of the pilot MCP actions, or situations, that invoke these autopilot goals are listed in italics for each set of autopilot goals.

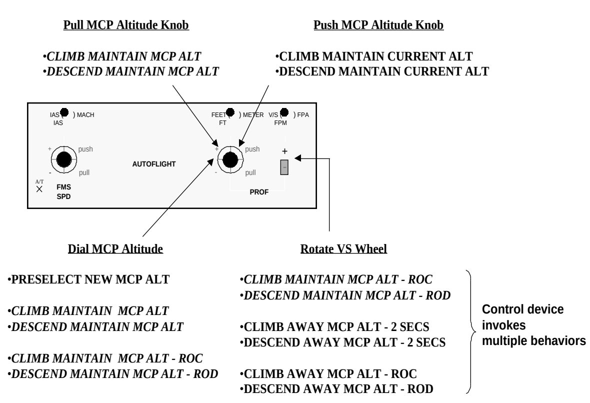
Autopilot Goals invoked by Direct Pilot Actions:

1. CLIMB MAINTAIN MCP ALT
2. DESCEND MAINTAIN MCP ALT
(Dial MCP Altitude Knob)
(Pull MCP Altitude Knob)
3. CLIMB MAINTAIN MCP ALT – ROC
4. DESCEND MAINTAIN MCP ALT – ROD
(Rotate MCP VS Wheel)
5. MAINTAIN CURRENT ALT
(Push MCP Altitude Knob)
6. CLIMB AWAY MCP ALT (2 SECS)
7. DESCEND AWAY MCP ALT (2 SECS)
(Rotate MCP VS Wheel)

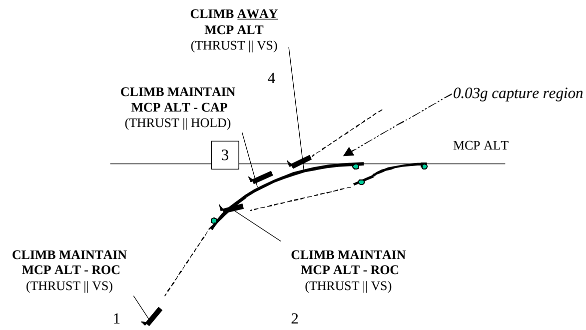
Autopilot Goals invoked Autonomously by Autopilot

8. MAINTAIN MCP ALT
(Aircraft is within +/- 60 ft and +/- 300 fpm of MCP Altitude)
9. CLIMB MAINTAIN MCP ALT – CAP
10. DES MAINTAIN MCP ALT – CAP
(Aircraft climbs descends within 0.03g Capture region to MCP Alt)
11. CLIMB AWAY MCP ALT
12. DESCEND AWAY MCP ALT
(Rotate MCP VS Wheel)
13. PROTECT SPEED ENVELOPE
(Aircraft violates speed envelope)

The pilot can invoke the first 7 goals through actions on the MCP. Goal pairs 1 & 2 perform flight level change with max thrust and idle thrust respectively. Goals 3 & 4 provide climb and descent with pilot selected rate of climb/descent. Goal 5 is for immediate level-off at current altitude. Goals 6 & 7 reflect a feature implemented in this autopilot that allows the pilot to "kill the capture" to the



MCP with autopilot labels for the goals that can be invoked by each MCP control device. Rotating the MCP Vertical Speed Wheel will result in one of three classes of autopilot behaviors depending on the situation.
Figure 2



Autopilot goals following rotation of the MCP Vertical Speed Wheel (1) prior to the capture region, (2) lower ROC in the capture region, (3) same ROC in the capture region, and (4) increased ROC in the capture region.
Figure 3

MCP altitude. Goals 8 -13 are invoked autonomously by the autopilot without any pilot confirmation. Goals 11 & 12 may b e invoked automatically by the autopilot 2 seconds after autopilot goals 6 or 7 are selected.

Figure 2 illustrates the MCP with the goals that may be invoked by pilot MCP actions on each control device. Italicized goals represent the same autopilot goal that can be invoked by more than one control device.

Different goals in the same box represent multiple goals that can be invoked by the same control device. Rotating the MCP Vertical Speed Wheel will result in one of three classes of autopilot goals:

- CLIMB/DESCEND MAINTAIN MCP ALT – ROC/ROD
- CLIMB/DESCEND AWAY MCP ALT – ROC/ROD (2 SECS)
- CLIMB/DESCEND AWAY MCP ALT – ROC/ROD

The goal that is invoked at any time is a function of the relative position of the MCP Altitude to the 0.03g capture region from the aircraft. Figure 3 diagrams the autopilot goals that will be invoked by the vertical speed wheel in each of 4 different situations.

5 MITIGATING "AUTONOMOUS MODAL" MCP CONTROL DEVICES

Using the goal-based framework described in Section 3, there are three ways in which the autonomous modal behavior of the MCP control devices can be addressed.

5.1 Place Knowledge in the World: Unique Control Devices for Each Goal

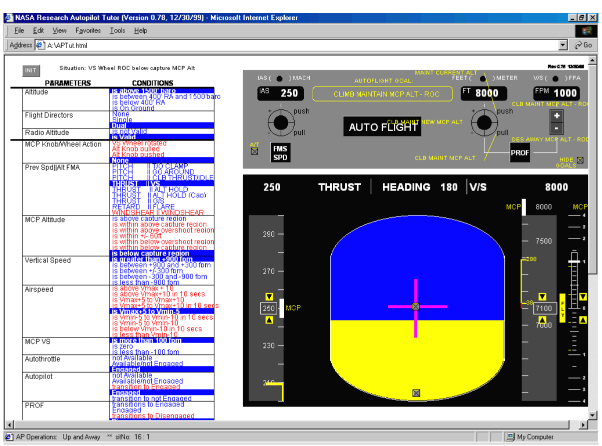
The simplest way to solve this type of automation surprise is to place knowledge in the world that makes the pilot task of conveying a goal to the autopilot intuitive and direct. A MCP/FCU designed with control devices that result in one, and only one, behavior satisfies this design criterion. Control devices for the pilot/autopilot goals CLIMB/DESCEND AWAY MCP ALT and CLIMB/DESCEND AWAY MCP ALT (2 SECS) would have to be added to the MCP to enable the crew to "kill the capture."

5.2 Place Knowledge in the World: Dynamic Goal Labels for Each Control Device

The second alternative is to include dynamic labels for each MCP control device that reflect the autopilot goal that will be invoked when the control device is selected. One implementation would be one-line liquid crystal displays for each MCP/FCU control device. In the case of the MCP Vertical Speed Wheel, the dynamic label would display one of the three goals listed above. As in the design of all user-interface components, the content and form of these goal label displays would have to considered carefully.

5.3 Place all Knowledge in the Pilots Head

When it is not possible to design the user-interface to place all the knowledge in the world, or when the system already is in place, it is necessary to train the operator. This training must explicitly define all the behaviors that can be invoked by each control device. Furthermore, this training should include the scan of necessary parameters



Autopilot Tutor. Trains pilots on situations-goals-actions of autpilot. Training requires students to execute ATC instructions in a LOFT. Training scaffolding and reinforcing feedback is provided.
Figure 4

to infer the correct situation and the knowledge to infer information that is not provided in the display directly.

Sherry, Feary, Polson, and Palmer (in press - b) developed a web-based Autopilot Tutor using the SGA model of the autopilot. Since the SGA model is created from the actual autopilot software it reflects the exact operation of the actual autopilot. Accompanying the tutor is a workbook with the definition of the autopilot goals, situations and behaviors. The workbook also includes LOFTs that require the pilot to perform flight scenarios that are designed to invoke all of the features and behaviors of the autopilot as defined in the SGA.

Two pedagogical features of the tutor that are worth noting are: (1) the tutor/workbook require the student to "solve problems" using the MCP by executing ATC instructions. This provides context for memory retrieval and is instrumental in converting declarative knowledge to procedural knowledge. (2) training scaffolding overlays additional icons on the Primary Flight Display. The scaffolding aids the student in learning what parameters are important and in building rich indexing schemes into long-term memory to retrieve patterns of the PFD for each situation in the SGA. One such scaffolding, is the display of the autopilot goal on the MCP. This provides immediate feedback to the student on which autopilot goal was invoked. The training scaffolding is faded as the training progresses to allow the student to transition to the actual cockpit.

6 CONCLUSIONS & RECOMMENDATIONS

A formal model for the NASA research autopilot software indicates that selection of the MCP vertical speed wheel may result in more than one autopilot behavior. During a capture of the MCP altitude, the MCP vertical speed wheel will invoke an autopilot goal to DESCEND AWAY MCP ALT - ROD (2 SECS) instead of DESCEND MAINTAIN MCP ALT. In the hypothetical example described at the start of the paper, the first-officer unwittingly "killed the capture" every time the MCP vertical speed wheel was selected.

The SGA model of the autopilot provides a formal method to identify the multiple autopilot goals that can be invoked using a single MCP control device. This method requires analysis of the actual automation software. Traditional task analyses, not grounded the actual behavior of the software cannot assure the safety of the system.

Solutions to the autonomous modal behavior of the MCP control devices can be addressed by: (1) use of unique control devices for each autopilot goal, (2) dynamic goal labels for each MCP control device, (3) and explicit pilot training to recognize the context-based behavior of each

MCP control device. The SGA model provides the necessary information for this training. The SGA model can be incorporated in an interactive web-based tutor that can be used to build and maintain pilot competency in the use of the automation.

6.1 Recommendation for Certification

The SGA analysis provides a formal method for evaluating the complexity of the context-based behavior of the avionics device. The model may be used to manufacturers to demonstrate to the certification authorities, the absence of this behavior in the MCP/FCU. The model is also useful to demonstrate the "traceability of requirements/code to sections of the training materials" (Palmer & Feary, 1999).

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